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Landform assemblages and sedimentary processes along the Norwegian Channel Ice Stream

Dag Ottesen^{a,*}, Chris R. Stokes^b, Reidulv Bøe^a, Leif Rise^a, Oddvar Longva^a, Terje Thorsnes^a, Odleiv Olesen^a, Tom Bugge^c, Aave Lepland^a, Ole B. Hestvik^d

^a *Geological Survey of Norway, P.O. Box 6315, 7491 Trondheim, Norway*

^b *Department of Geography, Durham University, Durham, DH1 3LE, UK*

^c *Det norske oljeselskap ASA, N-7011 Trondheim, Norway*

^d *Olex AS, Pirsenteret, P.O. Box 1256, 7462 Trondheim, Norway*

ABSTRACT

Several regional and detailed bathymetric data sets together with 2D and 3D seismic data are compiled to investigate the landform assemblages and sedimentary processes along the former path of the Norwegian Channel Ice Stream (NCIS). At the broad scale, the glacial geomorphology and sedimentary architecture reveals three different zones along the ice-stream path, characterized by: (1) glacial erosion in the onset zone and inner shelf area, (2) sediment transport through the main trunk of the ice stream across the mid-shelf, and (3) a zone of deposition towards the outer continental shelf edge. Along the first 400 km of the ice stream bed (outer Oslofjord-Skagerrak-Stavanger) a major overdeepening is associated with suites of crag-and-tail features at the transition to crystalline bedrock, together with evidence of glaciotectonic thrusting in the form of hill-hole pairs. Here we interpret extensive erosion of both sedimentary rocks and Quaternary sediments. This zone is succeeded by an approximately 400 km long zone, through which most of the sediments eroded from the inner shelf were transported, rather than being deposited. We infer that sediment was transported subglacially and is likely to have been advected downstream by soft sediment deformation. The thickness of till of inferred Weichselian age generally varies from 0 and 50 m and this zone is characterized by mega-scale glacial lineations (MSGs) which we interpret to be formed in a dynamic sedimentary system dominated by high sediment fluxes, but with some localized sediment accretion associated with lineations. Towards the shelf break, the North Sea Fan extends to the deep Norwegian Sea, and reflects massive sedimentation of glacial debris onto the continental slope. Numerous glacial debris flows accumulated and constructed a unit up to 400 m thick during the Last Glacial Maximum. The presence of these three zones (erosion, transport, deposition) is consistent with observations from other palaeo-

ice streams and their significance arises from their potential to feedback and impact on ice stream dynamics.

Keywords: Glacial lineations, glacial erosion, Norwegian Channel, palaeo-ice stream, sea-floor morphology

1. Introduction

The flow of continental ice sheets is partitioned between large areas of relatively low velocity ($<50 \text{ m a}^{-1}$) and narrower ‘arteries’ of much higher velocity ($>100 \text{ m a}^{-1}$), with tributaries that extend well into the ice sheet interior (Bamber et al., 2000). These rapidly-flowing zones are known as ice streams and they are viewed as an important control on ice sheet mass balance and stability (Hughes, 1977; Bentley, 1987; Stokes and Clark, 2001; Bennett, 2003). Given their significance, much work has been devoted to investigating the subglacial processes that facilitate their rapid flow, and recent advances in geophysics have enabled workers to image the bed of active ice streams (Smith, 1997a, b; King et al., 2007; Smith et al., 2007; Smith and Murray, 2009; King et al., 2009; Jezek et al., 2011; Ashmore et al., 2014). A key conclusion from these studies is that the ice-bed interface is highly dynamic, with sediment being eroded and transported over short (sub-decadal) time-scales, and in association with the evolution of subglacial bedforms, such as mega-scale glacial lineations (MSGs: King et al., 2009). However, the precise mechanism(s) of flow remain difficult to ascertain, e.g., basal sliding over the till versus deformation and advection of sediment to various depths (Alley et al., 1986; Engelhardt and Kamb, 1998; Tulaczyk et al., 2000). Moreover, borehole and geophysical investigations of active ice streams are typically limited to just a few sites, making it difficult to investigate sedimentary processes along the entire ice stream bed. In contrast, numerous workers have recognized the potential to glean insights about subglacial processes beneath ice streams by investigating well-preserved palaeo-ice stream beds, either proximal to modern-day ice sheets in Greenland (Evans et al., 2009; Ó Cofaigh et al., 2013, Dowdeswell et al., 2014) and Antarctica (Livingstone et al., 2012; Graham et al., 2009; Ó Cofaigh et al., 2002, 2005), or from the beds of the last mid-latitude ice sheets (Andreassen et al., 2004; Ottesen et al., 2005, 2008; Rydningen et al., 2013; Margold et al., 2015). Palaeo-ice stream beds are easily recognizable by a distinctive glacial geomorphological imprint, compared to slow-flowing regions outside of the ice stream, especially in areas where till is thick enough to be moulded into subglacial bedforms (Dyke and Morris, 1988; Stokes and Clark, 1999, 2001). Characteristic landforms on these ‘soft-bedded’ ice stream beds

include high elongate mega-scale glacial lineations (MSGs) (Clark, 1993; Spagnolo et al., 2014) and ice stream shear margin moraines (Dyke and Morris, 1988; Stokes and Clark, 2002). Along continental shelves that fringed palaeo-ice sheets, ice streams also carved large cross-shelf troughs (Shaw et al., 2006; Rydningen et al., 2013; Batchelor and Dowdeswell, 2015), often associated with grounding zone wedges that mark their terminus position (Dowdeswell and Fugelli, 2012; Evans and Hogan, 2016), and trough-mouth fans that attest to large volumes of sediment transport (Vorren and Laberg, 1997; King et al., 1996; Nygård et al., 2007). In areas devoid of till cover, 'hard-bedded' ice streams are more difficult to identify, but recent work suggests that mega-lineated terrain (including rock drumlins and bedrock mega-grooves) is produced by enhanced abrasion and quarrying of bedrock (Roberts and Long, 2005; Bradwell et al., 2008; Eyles, 2012; Krabbendam et al., 2015). Thus, these landform assemblages offer potential to understand sedimentary processes and flow mechanisms beneath ice streams over much larger spatial scales than is possible from geophysical investigation of modern ice streams.

One of the best-preserved and largest palaeo-ice streams yet reported was located in the Norwegian Channel (NC), the Norwegian Channel Ice Stream: (NCIS), which represents one of the most important ice and sediment discharge routes from the former Fennoscandian Ice Sheet. Its trough extends for >800 km from near its source area in southern Norway and Sweden, and is >100 km wide at the edge of the continental shelf (Fig. 1). In this paper, we describe the landform assemblages along the entire length of this palaeo-ice stream system and its marginal areas. Our data sources benefit from over four decades of hydrocarbon exploration and we also take advantage of several new datasets to explore the sedimentary processes, with a particular focus on the identification of zones of erosion, transport and deposition at the local Last Glacial Maximum.

2. Geological background and previous work on the Norwegian Channel Ice Stream

The Norwegian Channel Ice Stream (NCIS) was first postulated by Helland (1885), largely based on the presence of bedrock clasts in clays from the Jæren area that were sourced from the Oslofjord region (Fig. 1). He claimed that these clasts were incorporated in a till deposited by a 'Skagerrak-glacier' which moved westwards from the Oslofjord area and south-central Sweden along the axis of the Skagerrak Trough parallel to the Norwegian coast around southern Norway and into the Jæren area (Fig. 1). However, Andersen (1964) later questioned this interpretation, instead arguing that the clay-rich 'Skagerrak till' was a glaciomarine deposit with dropstones. The notion of a NCIS was later reinvigorated when Rokoengen and

Rønningsland (1983) documented north-flowing ice in the northern part of the NC based on seismic data.

Around 1980, the British Geological Survey (BGS) and the Norwegian Continental Shelf Institute (IKU, now Sintef Petroleum Research) initiated a mapping program of shelf areas in the North Sea. A series of seabed and Quaternary geology maps (scale 1: 250 000) covering the whole UK part of the North Sea were produced, and a regional Plio/Pleistocene stratigraphical framework was developed with a series of lithostratigraphic units of regional extent (Stoker et al., 2011). IKU covered the northern North Sea with high-resolution single-channel shallow seismic data and produced a Quaternary geological map of the northern North Sea at a scale of 1: 500 000 (Rise et al., 1984). Rise and Rokoengen (1984) mapped the seabed sediments and the shallow seismic stratigraphy in the Norwegian sector of the northern North Sea (60°30'-62°N) based on a regional high-resolution seismic grid, grab samples and vibrocores. They reported a generally thin layer of Holocene sediments (< 1 m thick, most often less than 30 cm in thickness) on the North Sea plateau, west of the NC, which was generally less than 2 m in thickness in the deepest parts of the NC. In the central part of the NC a total thickness of up to 40 m of normally consolidated clay was found. Except for the thin Holocene unit, the clay was deposited during the deglaciation after the ice stream retreated (and denoted as 'late-glacial' clay).

On the northern part of the North Sea plateau, over-consolidated clays with till-like composition were sampled (Rise and Rokoengen, 1984). Core A79-156 (location shown on Fig. 1) is topped by a 50 cm thick sandy layer with a ¹⁴C-date close to the base giving an age of c. 14 kyr BP and, below that, a 50 cm thick sandy unit with three dates around 35 kyr BP. Core A79-146 (Fig. 1) revealed a c. 20 cm thick Holocene layer above a clayey unit (20 cm) and, under that, 140 cm of stiff clay was interpreted as a till with a shell dated to c. 23 kyr BP. The ¹⁴C-ages younger than 21,000 ¹⁴C years are converted to calendar ages using the U/Th calibration curve of Fairbanks et al. (2005). Older ages are converted to calendar years by adding 4000 years to the ¹⁴C age (Olsen et al., 2001).

Rise and Rokoengen (1984) also suggested that the till unit deposited by the NCIS in the NC extended onto the plateau to the south and west. Parts of the till were interpreted to have been removed by subsequent erosion, leaving a lag of stones and boulders on the plateau. The content of rocks from the Oslofjorden area in one area near Statfjord (Dekko, 1977) could either be explained by transport by the NCIS or by deposition from icebergs. The dates in core A79-156 show that the area was ice-free during parts of the Ålesund Interstadial (34-38 kyr BP, Mangerud et al., 2010) and the date from core A79-146 shows that the area must have

been ice covered c. 23 kyr BP. Rise and Rokoengen (1984) also suggested northward flowing ice in the NC based on the morphology of the LGM surface at the base of the Norwegian Channel. They found ridges and depressions with a general NNW-SSE trend, and interpreted the ridges as medial moraines formed between ice flow from the Norwegian coast in a NNW direction and the main ice stream following the main axis of the NC.

Despite this large body of work, it was not until the mid-1990s that the concept of the NCIS became widely accepted. Longva and Thorsnes (1997) documented evidence of the NCIS in Skagerrak (the onset zone), describing extensive glacial lineations attributed to several ice flow phases across the area. Further down-stream, Stalsberg et al. (2003) mapped several coast-parallel ridges in Jæren and interpreted them as drumlins, arguing that the NCIS flowed across the lower elevation areas of the coast during the last glaciation. Rise et al. (2008) discussed the deglaciation after the collapse of the NCIS in the Skagerrak area, and described a thick (up to 250 m) sequence of mainly layered sediments.

Distal to the ice stream's channel, King et al. (1996) mapped the internal structure of the North Sea Fan (NSF, Fig. 1) based on a regional net of high-resolution 2D seismic lines. They showed that the NSF comprises more than 900 m of sediments with numerous sequences including four large translational slides. They attributed this to periodic input from several phases when the NCIS reached the shelf edge, with the last dated to the Late Weichselian. Later work by King et al. (1998) described a suite of stacked sediment units of lensoid and lobate forms (2-40 km wide and 15-60 m in thickness) and termed these units 'glacigenic debris flows' (GDFs). Sejrup et al. (2003) provided a comprehensive review of the configuration, history and impacts of the NCIS, suggesting that the NCIS only reached the shelf edge after the Sandnes/Ålesund interstadials (c. 34-38 kyr BP) during the Weichselian glaciation. This implies that the NCIS only operated around the LGM of the Weichselian glaciation. Lekens et al. (2009) dated the main development of the North Sea Fan during the last glacial cycle to have occurred after 30 kyr BP. From around 24 kyr BP the NCIS became very active and advanced at least three times prior to the final retreat from the shelf edge around 19.0 kyr BP (Nygård et al., 2007; Lekens et al., 2009). The island of Utsira, located c. 400 km south of the outlet of the NC, was ice free around 20 kyr BP (Svendsen et al., 2015), documenting that the ice retreat after the last sediment pulse of the NCIS must have been very rapid.

Building on this body of work, our paper presents several new datasets of both regional and detailed bathymetry, 2D and 3D seismic and side-scan sonar data along the

whole 800 km path of the ice stream from the onset zone in Skagerrak to its LGM terminus at the shelf edge outside western Norway.

3. Data acquisition and methods

3.1. Data Sources

Several regional bathymetric datasets have been utilized for the sea floor morphology (Fig. 2). Parts of the study area are covered by a large dataset collected by single beam echosounders (100 kHz) during the years 1965-1985 by the Norwegian Hydrographic Service. The line spacing is 500 m and the data were gridded with a cell size of 500 m. This dataset provides a useful regional overview of the sea floor morphology. The dataset is visualized as colour or grey-shaded maps, sometimes supplemented with 10 m depth contours.

Most of the Skagerrak is covered by multibeam bathymetry (MBB) (c. 8,000 km²) collected by the Norwegian Hydrographic Service during the years 1990 to 1995 with an EM100 echosounder (95 kHz, 32 beams). Water depths covered are between 100 m and 700 m. The whole dataset was gridded with a cell size of 50 m, whereas certain subareas were gridded with 10 m cell size.

The Norwegian Defence Research Establishment (FFI) collected a large dataset of MBB during the years 2003-2008 (Eidem and Landmark, 2013) with a Kongsberg Maritime EM 1002 echo-sounder. This equipment has 111 beams and 2° x 2° beam width. The dataset covers the coastal areas of western Norway between Bømlo and Sognefjorden (59°30'N-61°N) up to 60 km off the coast (to c. 4°E), covering an area of c. 10,000 km² (Supplementary Fig. 1).

Two regional 50 m bathymetric grids from Olex AS have been utilised (www.olex.no). These data sets are based on single-beam echo-sounder data collected by numerous types of commercial vessels and later delivered to Olex where the data have been processed (tide adjusted and leveled) and gridded. One dataset covers the coastal areas from Sognefjorden to Møre inside 12 nautical miles; the second data set covers the Tampen area and including the North Sea plateau west of the NC and parts of the outer NC itself.

Approximately 10 km outside the coast west of Sognefjorden, the Norwegian Hydrographic Service collected a high resolution MBB dataset with a Simrad EM-100 echo-sounder in 1998. The dataset was gridded with a 2 x 2 m cell size and covers an area of 3 x 10 km.

During 1982-1985, the Norwegian Hydrographic Service collected side scan sonar (SSS) data in the NC and on the northeastern part of the North Sea plateau (Egersundbanken)

(Ottesen et al., 2000). The dataset comprises north-south oriented lines with a line spacing of 500 m. The sonar applied was a Klein 531T dual, mainly operated at 50 kHz and displaying 300 m of the seafloor to each side of the towed fish. The data were printed on paper, and the dataset covers an area of about 25,000 km². The interpretation of the sea-floor composition was based on sea-bed reflectivity (Lien, 1995; Ottesen et al., 1998). More resistant substrates (e.g., overconsolidated tills) result in strong reflectivity, whereas softer sediments give weaker reflectivity. Sea-floor morphology, such as glacial lineations, iceberg ploughmarks, pockmarks and sand waves can be observed in the side scan records. The SSS interpretations reveal low reflectivity (soft substrates) in sandy areas of the North Sea plateau and in areas with fine-grained sediments in the NC, whereas high reflectivity occurs in areas of harder substrates (till, overconsolidated clays, lag deposits) on the North Sea plateau.

Several seismic lines along the coast and across the NC have been utilized. The Norwegian Petroleum Directorate collected seismic data on cruises during the 1990s off the west coast of Norway, crossing the transition zone between crystalline and sedimentary rocks, and located a few kilometres from the coast. Some of these lines also continue into the fjords. These high-resolution seismic lines were digitally recorded and visualized and interpreted with Petrel software.

Several 3D seismic cubes in the NC and on the North Sea plateau have also been used. Petroleum Geo-Services (PGS) compiled a mega-survey of a large number of individual 3D seismic surveys covering about 40,000 km² of the Norwegian North Sea and 50,000 km² of the British North Sea. The seismic bin size of the cubes is 25 x 25 m and the vertical sampling is 4 milliseconds (c. 3 m). We have used some of these cubes to look for glacial lineations or other glacial features on the seafloor and on buried surfaces. MOS2007 (PGS) is a relatively large 3D seismic cube (c. 1500 km²) located close to the shelf break in the outer part of the NC and also covers parts of the North Sea Fan. The 3D-seismic data have been interpreted and visualised in Petrel software.

Between 1991 and 1995, approximately 20,000 km of shallow seismic profiles were collected in Skagerrak during cooperative cruises by the Norwegian Hydrographic Service and NGU. The profiles were either located in a regional grid (mostly 10 km spacing between the lines), or were collected simultaneously with the swath bathymetry data. The energy sources used were sleeve guns (5-40 inches³) recorded down to 1 second two-way travel time (twt) and a high-resolution Geopulse boomer system, giving better resolution in the upper strata (Longva and Thorsnes, 1997; Ottesen et al., 2000).

We have also accessed a large database of commercial 2D seismic lines. The late Weichselian till surface has been interpreted on most of these lines in the Petrel software. The interpreted reflector was gridded, and the horizon was merged with the late Weichselian erosion surface of Rise et al. (2008) from Skagerrak.

Cores and data from several geotechnical boreholes (20-50 m long) on the eastern North Sea plateau have also been studied. These were collected at the Yme oil field (block 9/2) in connection with site survey investigations (NGI, 1993).

3.2. Mapping approach

Based on the single- and multibeam bathymetric datasets described above, we generated geo-referenced Tif-images, either colour- or grey-shaded and, in some cases, with depth contours (using various softwares such as Geosoft, ErMapper or Fledermaus). These images were imported into an ArcGIS project, where glacial features on the sea floor were mapped and digitized. In addition, several 3D-seismic cubes were imported and interpreted in the Petrel software. The seabed within the cubes was interpreted and then gridded (10 m or 25 m cell size). Buried surfaces were interpreted and the data were imaged in the same way as the single- and multibeam data sets and imported into the same ArcGIS project. The digital 2D seismic lines were interpreted in Petrel. Some lines are presented together with the bathymetry to support the analysis of the sea floor morphology and the Quaternary stratigraphy. The side-scan sonar data sets were manually interpreted in several projects (Lien, 1995; Ottesen et al., 1998). Based on these data sets, a seabed sediment map was produced, and glacial features were interpreted (Ottesen et al., 1999; Ottesen et al., 2000). All these results were transferred to the regional ArcGIS project as Shapefiles.

4. Results

We present our results according to five main regions of the ice stream (Fig. 1): (i) the onset zone in Skagerrak, including the Arendal Terrace, (ii) the southwestern lateral margin of the ice stream, (iii) the eastern marginal zone of the ice stream along western Norway, including Karmsundet and outer Boknafjorden and the coastal zone south and north of Bergen, and (iv) the central and northern area of the ice stream, including the outer trough. We then present some results from (v) the North Sea plateau.

4.1. Ice stream onset zone in the Skagerrak

In this study we present several bathymetric datasets from the transition zone between crystalline and sedimentary bedrock, which usually occurs a few kilometres off the Norwegian coast. The morphology of the seabed strongly reflects this transition, especially where the bedrock has a thin cover of Quaternary deposits.

4.1.1. Eastern Skagerrak

Skagerrak is the deepest part of the North Sea with water depths exceeding 700 m (Fig. 1). In the eastern (inner) part of the Skagerrak, at the boundary between crystalline and sedimentary rocks, a well-developed pattern of slightly curving, elongate ridges and depressions, generally a few kilometres long (but up to 10 km) are developed (Fig. 3). The pattern is one of convergence over a 100 km wide zone, initiating in water depths of 400-500 m. It can be followed 125 km downflow from the transition zone to the western boundary of the dataset. The spacing between ridges is 200-450 m, and the height of individual ridges can reach 15 m, but is usually less than 5 m.

In the southeastern Skagerrak, in water depths of 500-600 m, several curved or elongated depressions occur east of and on top of a 100 m high, 10-15 km wide, and 20 km long transverse bedrock ridge (Fig. 4). The most pronounced depression has the form of a hairpin with two parallel sides and a bend in the northeast ('a' on Fig. 4A). The sides of the hairpin are sub-parallel, c. 5 km long and c. 800 m apart. The deepest SE-side of the hairpin is c. 300 m wide and 20 m deep at the NE end; it narrows to c. 100 m width and 10 m depth towards the SW. A similar but more open hairpin depression ('b' on Fig. 4A) has a total length of c. 5 km, width of 150-300 m, and depth of 10-40 m. A series of partly connected curved depressions occur along the eastern slope and base of the transverse bedrock ridge. They appear to follow the strike of outcropping bedrock in NNW-SSE-direction, and are up to 30 m deep and 300 m wide. Some shallower depressions with a more NE-SW trend are located at the very top of the bedrock ridge. These can be up to 25 m deep and 300 m wide.

Several pairs of depressions and mounds are found in the deepest part of eastern Skagerrak (Fig. 5). The largest depression is 8 km long, 4 km wide and 30 m deep, in 650 m water depth. The long sides of the depression are sub-parallel with a NE-SW-trend. Within the depression, there are several smaller ridges and elongated depressions sub-parallel to the long sides of the larger depression. These ridges are up to 5 m high with an average width of c. 300 m. Immediately southwest of the large depression, there are two oval-shaped mounds that are up to 40 m high and with a total area of c. 15 km². Similar NE-SW trending depressions, mounds and ridges are found further east, where the depressions are up to 10 km long and with an

average internal distance of 330 m (Fig. 5). Southwest of the lineations, two mounds up to 20 m high, each covering c. 3 km², occur. A seismic line crosses one of these mounds (Fig. 5E), showing that above the bedrock surface, a 30 m thick mounded seismic unit appears. On top of this, there is a parallel laminated unit more than 50 m thick mimicking the underlying surface.

Similar SE-NW trending depressions occur in 500-570 m water depth, east of the 100 m high bedrock ridge mentioned above, and marked with D in Fig. 4A. The largest depression is 8 km long, 4 km wide and up to 30 m deep, and within it there are up to 15 parallel ridges less than 5 m high, with an average distance of 230 m. The length:width ratio of the large depressions is usually around 3:2. They form part of a NE-SW trending lineated pattern across the whole eastern Skagerrak.

4.1.2. Arendal Terrace

The Arendal Terrace is a prominent SW-NE trending sediment deposit of about 800 km² located along the northwestern flank of the Skagerrak (Longva and Thorsnes, 1997; Sejrup et al., 2003; Ottesen et al., 2005; Bøe et al., 2016) (Fig. 6). The sediment deposit is nearly 80 km long, reaching 18 km wide in the central and northeastern parts. The terrace narrows towards the southwest to less than 3 km. It comprises up to 300 m of acoustically layered Quaternary (pre-late Weichselian) deposits capped by till and draped by glacial-marine and Holocene marine deposits (Fig. 6). The surface of the terrace is irregular with water depths between 400 and 500 m. It has a steep margin of 6-8° down to the deepest part of the Skagerrak Basin at c. 700 m in the southeast. The lower slope is locally without till or any fine-grained drape, and pre-late-Weichselian deposits and sedimentary bedrock may locally be exposed (Bøe et al., 1996).

The surface of the terrace comprises a series of hills, ridges and depressions (Fig. 6). Elongate ridges trend southwest-northeast and are up to 20 km long and 30 m high, displaying a slightly curved pattern with their convex sides to the southeast and a convergent pattern towards the southwest (Bøe et al., 2016). Elongate depressions can be up to 5 km long, 2 km wide and 50 m deep, but are generally less than one kilometre in width. They show complex patterns and depressions may have hills to the southwest linking the ridges on either side. In other areas, several parallel depressions may be separated by saddles only a few metres high, ending in large undulating-ridge complexes towards the southwest. Iceberg ploughmarks locally cut into the surface of the terrace, especially along its southeastern edge.

4.2. *Southwestern margin of ice stream*

Based on interpretations of SSS data of the eastern North Sea plateau (Egersundbanken) and the NC, a seabed sediment map was compiled by Ottesen et al. (1999) (Fig. 7A). A regular pattern of parallel, elongated, SE-NW trending ridges and depressions (alternating light and dark areas in the SSS data) occurs along the northeastern margin of the North Sea plateau. Ridges are represented by the dark areas (hard sediments), whereas light areas represent sand that covers areas between ridges (Fig. 7B). To the southwest, on the North Sea plateau, smaller areas with a similar pattern occur, but there ridges and depressions trend ENE-WSW (Fig. 7C).

Two hundred vibrocores were collected on the eastern North Sea plateau (4-6°E, 57-58°N) in 1997 by Surface Geochemical Services (Ottesen and Bøe, 1998). Core lengths are up to 3.6 m with an average of 2.2 m. Thirty eight of the cores have been previously opened and described (Ottesen and Bøe, 1998). The cores frequently comprise up to 50 cm of sand in their upper parts. ¹⁴C dating of shells from the sand (unpublished data by the authors) has given Holocene ages indicating very thin or no Holocene deposits in these areas of the North Sea plateau. Below the sand, clayey sediments or a mixture of layers of clay and sand are found.

In 1993, while evaluating the possible development of the Yme oil field (Block 9/2) on Egersundbanken (Fig. 7A), several geotechnical boreholes were drilled up to 50 m deep (NGI 1993). Lithological logs from two of the boreholes are compiled in Fig. 7D. The boreholes were not continuously cored; the logs in Fig. 7D are partly based on cone penetration test (CPT) data. Over distances of 1-2 km, the stratigraphy in the upper part of the seabed changes dramatically. The investigated cores exhibit a unit of medium grained sand (occasionally fine grained and silty) in their upper part, varying in thickness from 2 to 22 m (NGI, 1993). Sedimentary structures such as sand ripples, laminations, cross bedding and syn-sedimentary deformation structures are common.

Both cores contain layers and thicker units of olive grey to dark brown stiff to very hard clay with lamina and lenses of silt and sand in their lower parts. Several cored intervals (a.o. 18-25 m in BH1004) contain tectonized sediments with folds, shear structures and faults (Fig. 7E) that can be classified as till. Undrained shear strength (s_u) measured in the clay units increases downwards in the boreholes, e.g., from 100-200 kN/m² at 8 m depth, to 400-550 kN/m² at 24 m depth in BH1004. Two ¹⁴C dates of shells in the till at 19.55 m depth in BH1004 (Fig. 7D) gave ages corresponding to the Ålesund and Bø interstadials (Mangerud, 2004; Mangerud et

al., 2010), c. 38 kyr BP (34.4 ± 0.5 ^{14}C kyr BP) and 52 kyr BP (47.8 ± 2.6 ^{14}C kyr BP), respectively.

4.3. Eastern ice stream shear marginal zone along western Norway

A remarkable suite of glacial landforms has been mapped along the 400 km long coast of western Norway between Stavanger (59°N) and Stad (62°N). These landforms are described in the following paragraphs based on bathymetric data and 2D seismic lines.

4.3.1. Karmsundet and outer Boknafjorden

The Karmsundet Basin is a down-faulted half-graben with Mesozoic rocks between the island of Karmøy in the west and the mainland, including a bedrock threshold at the outlet of Boknafjorden, in the east (Bøe et al., 1992). The basin occurs below a N-S-trending trough starting east of Karmøy and widening towards the south that is up to 5 km wide and 30 km long. The trough turns west and thereafter northwest c. 20 km south of Karmøy, feeding into the NC (Fig. 8). The trough reaches a maximum water depth of c. 350 m and is filled in by an additional 250 m of Quaternary sediments (Fig. 8B). These sediments comprise mainly late-glacial and Holocene sediments with a contouritic appearance and locally till above bedrock (Bøe et al., 1992, 2000). A seismic line across the trough shows that its southern boundary is in a thick package of tills and layered sediments above bedrock (Fig. 8C, D). Two of at least three till units are probably of pre-Weichselian age. Several onshore boreholes from the Jæren area document a complex Quaternary stratigraphy with several till units with interbedded material, documenting at least four ice-free periods with marine deposition during the last 200 kyr BP (Sejrup et al., 1998).

4.3.2. Coastal zone south of Bergen

Four large curving ridges (labelled R1-4) developed in Quaternary sediments have been mapped in the coastal zone south of Bergen (Fig. 9). The ridges initiate at the boundary between crystalline and sedimentary rocks approximately 10 km from the present coast. They trend towards the northwest and then bend towards the north farther away from the coast. R1 is flat topped, 10 km wide, up to 20 m high and more than 50 km long, whereas R2 is 5 km wide and up to 30 m high. These two ridges merge before they become indistinct several kilometres farther north. R3 is up to 5 km wide and 70 m high. After 20 km it disappears, but seismic data suggest that it may continue below younger sediments. R4 is 6 km wide, up to 60 m high, and has a length of 35 km. Between the ridges, especially between R3 and R4, but

also north of R4, there are several sub-parallel, smaller ridges. A pattern of linear to curvilinear depressions is developed on top of the large ridges. In the depression between the outer parts of R3 and R4, many circular or elongated depressions up to 200 m wide and a few metres deep are found (Fig. 9A). Two large and several smaller fjords are cut deeply into the crystalline bedrock in the coastal zone. Korsfjorden is more than 600 m deep, whereas Selbjørnsfjorden is up to 400 m deep.

A seismic line across the ridges (Fig. 9B) shows that west of the boundary between crystalline and sedimentary rocks, late glacial and Holocene sediments rest directly on the sedimentary rocks. Approximately five kilometres farther west, the thickness of older Quaternary deposits increases rapidly to a few hundred metres. A sequence of flat lying units, often transparent in appearance but occasionally also layered, occurs above the Upper Regional Unconformity (URU).

4.3.3. Coastal zone north of Bergen

In this area, a well-developed pattern of lineations initiates around 15 km offshore, east of the boundary between crystalline and sedimentary bedrock (Fig. 10). The lineations trend east-west close to the coast, but turn towards the northwest and then north. The average distance between the ridges is 400-600 m, and their height is generally less than 10 m. To the east, the crystalline bedrock is partly covered by a thin layer of Quaternary deposits (mostly Weichselain till) (Fig. 10B). Farther out, the stratigraphy is more complex with a succession of flat-lying units (mostly till with layered marine/glaciomarine units between) above the URU. The flat-lying units are partly eroded in the east. Below the URU, westward dipping sedimentary strata of Jurassic to Neogene age are found (Riis, 1996; Sigmond, 2002).

In an area northwest of Sognefjorden, the Øygarden Fault Zone represents the boundary between Mesozoic sediments to the west and Paleozoic sedimentary rocks or crystalline basement rocks to the east (Fig. 11). West of the fault zone, Quaternary deposits are around 250 m thick (Rise et al., 1999). Only a thin and discontinuous layer of Quaternary sediments occurs on top of the basement rocks, which crop out at shallower depths with a pronounced seafloor relief. A well-developed pattern of sub-parallel NW-trending ridges occurs in the Quaternary deposits (Fig. 11). In the east, the ridges start in approximately 250 m water depth, where they are up to 600 m wide. Towards the west, they become more subdued before disappearing around 370 m water depth, in the western part of the mapped area. Six ridges can be seen with an average internal distance of 450 m. Along the slopes of some of the

ridges, arcuate scars up to 1400 m long and 40 m high are developed (marked S on Fig. 11). In front of the scars, piles of hummocky deposits occur.

4.4. Central and northern Norwegian Channel and outer trough

The NC off western Norway is generally covered by lateglacial/Holocene sediments masking glacial features on the LGM till surface. We inspected several 3D-seismic cubes to study buried glacial landforms and present data from one cube (L09, PGS megasurvey) located close to the western slope of the channel west of Sognefjorden (Fig. 1). Data were extracted from both the seabed and a well-defined, buried surface (Fig. 12). A laminated unit up to 50 m thick occurs above the buried surface, which undulates across a major NNW-SSE trending ridge with elongated depressions on both sides. The ridge is up to 20 km wide and 50 m high, and can be followed for more than 300 km on the regional bathymetry (Fig. 12B). The surface displays an extensive pattern of lineations with a general trend NNW-SSE. The lineations are generally < 10 km long and up to a few metres high, although some ridges reach lengths of up to 25 km. In addition to these parallel lineations, a pattern of curvilinear features are found. Although this pattern is to some extent irregular, an overall north-south trend can be found.

A regional seismic profile (Fig. 13A) shows the stratigraphy of the North Sea Fan, which has the appearance of a large and complex prograding sequence. The Base Naust reflector (Fig. 13A) represents the base Quaternary. In this part of the fan, a thickness of up to 1600 milliseconds is observed (equalling 1600 m assuming an average sound velocity of 2000 m/s), although up to 1800 m have been reported (Nygård et al., 2005). The shelf edge has prograded up to 50 km during the Quaternary. Figure 13B shows a seismic cross-section of the upper part of the North Sea Fan (from the 3D cube MOS2007) (Fig. 1). On a regional scale, the units have a generally layered appearance, but closer inspection reveals that the units are stacked with lensoid and lobate shapes. Some units are separated by packages with a structureless or chaotic appearance (green and orange colours on Fig. 13A and B). Above the green unit, up to 400 m of sediments have been deposited. The reflection marking the base of the green unit is stepping upwards towards the apex of the fan (Fig. 13B), and two transparent units (E and S on Fig. 13B; the lowermost E is up to 200 ms thick) are cut by this reflector. We have extracted data from two buried surfaces in the cube and generated seismic amplitude maps for each surface (Fig. 13C, D). Surface A is below the uppermost transparent unit, whereas B is on top of this unit.

A strong pattern of slightly curving lineations is observed on both surfaces. The lineations trend 155-335° on surface A and 162°-342° on surface B. The uppermost step in the reflector below the Tampen Slide has been mapped (yellow stippled line on Figs. 13 C, D). The lineations stop at this line on surface A, but are found up to 10 km north of the line in surface B. The lineations are developed along a 35 km long distance on surface A, and along 40 km on surface B.

4.5. North Sea plateau

The surface of the plateau areas west of the NC are dominated by sediments from the last deglaciation and the Holocene. This period was dominated by marine processes in a shallow sea, which generated large areas with sandy sediments and beach deposits, such as beach ridges in the transition zone between land and sea (Rokoengen et al., 1982). Rokoengen et al. (1982) described a submerged beach at 130-160 m water depth bordering the northern part of the North Sea plateau towards the NC. The beach deposits are parallel to the western margin of the NC for at least 50 km. Due to the surficial deposits, it is difficult to find evidence of glacial activity such as glacial lineations, iceberg ploughmarks or glaciotectonic features on the seabed.

Several 3D cubes have been studied in a search for buried surfaces with glacial features. In cube H08 (part of the PGS megasurvey), around 59°N and 2°30'E in c. 120 m water depth, a pattern of sub-parallel lineations trending NE-SW for at least 8 km c. 100 m below the seabed is found (Fig. 14, see also Fig. 7). The linear features have a divergent pattern towards the southwest. The main trend is 245°, changing to 230° in the southern part. The linear features occur just above two slightly curving, buried channels. These channels are up to 1 km wide and 170 m deep, and extend across most of the area (marked T1 and T2 in Fig. 14). The infill in the channels has a seismic character different from the surrounding sediments.

Along the outer western margin of the NC in the Tampen area, a ridge forms a prominent topographic feature along the edge of the plateau (Fig. 15). It stretches from the south at c. 61°N in 125 m water depth and continues towards the northwest for c. 165 km, ending close to the shelf edge at c. 250 m water depth. The ridge is c. 10 km wide and up to 25 m above the surrounding North Sea plateau towards the northwest.

The Quaternary stratigraphy of the area shows several units dipping towards the east (Fig. 15B), and the uppermost unit along the eastern plateau edge is named the Tampen Formation and reaches a maximum thickness of 50 m (Rise et al., 1984; Skinner et al., 1986). The unit

comprises soft to firm to very stiff clays with sands and pebbles. ^{14}C dating of shells from this unit has given an age of 23 kyr BP (18.860 ± 0.260 ^{14}C kyr BP), (Rokoengen et al., 1982).

West of the Tampen ridge, on the northwest-sloping seafloor, at least two slightly curving ridges occur. The northernmost and E-W trending ridge is 50 km long and up to 10 km wide, in 170 to 180 m water depth (Fig. 15A). In the outer parts of the NC, several transverse ridges appear. The ridges are up to 70 km long, 15 km wide and 25 m high.

5. Interpretation

5.1. Ice stream onset zone in the Skagerrak

5.1.1 Eastern Skagerrak

The linear features in Fig. 3 are interpreted as glacial lineations. Where they initiate from bedrock high-points they fit the description of large crag-and-tails, but the dimensions and low amplitudes of the features down-stream of the bedrock transition fit the description of mega-scale glacial lineations (Clark, 1993; Spagnolo et al., 2014). The MSGs are especially well developed in the deepest part of Skagerrak, where the ice stream eroded extensively into both Quaternary sediments and the underlying sedimentary bedrock. The onset zone for the ice stream was at the transition between crystalline basement and Mesozoic rocks in the inner Skagerrak, east of the Arendal Terrace.

The pattern of convergence indicates strong influx of ice from a large drainage area on mainland Norway and Sweden and, after crossing the boundary between crystalline and sedimentary rocks, the ice stream likely accelerated, which facilitated enhanced erosion of the Quaternary sediments and the sedimentary Jurassic and Cretaceous bedrock. The MSGs are developed on top of the bedrock surface or on the overlying till surface, or on top of the irregular topography interpreted to be glaciotectonic thrust features (Fig. 5E). This surface is generally covered by an up to 70 m thick unit of layered lateglacial and Holocene sediments. Longva et al. (2008) reported an up to 80 m thick drape of glaciomarine sediments along the southern slope of the NC. Because of the uniformity of this drape, the upper surface of the sediments beneath is mimicked on the present sea floor.

In addition to erosion by abrasion and quarrying of the boundary of the crystalline bedrock, we interpret the hairpin features (Fig. 4) to indicate localized erosion by subglacial meltwater at high pressure (Shaw, 1994). The location of the features just behind the large bedrock ridge perpendicular to the general ice flow is likely to have enhanced water pressures to generate these features. We interpret them as being scoured by localized meltwater (cf., Anderson and

Fretwell, 2008), rather than more catastrophic floods (sensu Shaw, 1994) given that there is limited independent geomorphological or sedimentological evidence for more extensive floods. The generation of large amounts of subglacial meltwater would have been enhanced by the additional roughness on the crystalline bedrock surface (Peters et al., 2006) upstream from Skagerrak.

Consistent with the notion of accelerating flow in this region, are the series of paired depressions and mounds that occur downstream of the edge of the crystalline bedrock (Fig. 5). We interpret these depressions to have been formed by large-scale erosion, perhaps associated with glaciotectonic stick-slip behavior (Graham et al., 2009). The depressions are elongated in the ice-flow direction and glacial lineations can be found both on the sides of the depressions and in the depressions. We interpret the depressions to reflect large slabs of bedrock being thrust up from the sedimentary bedrock and disintegrated and assimilated into the moving layers below the ice stream along the ice stream path. Given enough time, these slabs are likely to disintegrate and be removed, but we observe some of them preserved, suggesting that they may have been deposited immediately prior to ice stream shut-down. Sættem et al. (1994) documented that a 15-25 m thick block of Cretaceous sedimentary rocks was buried in a Pleistocene till in the Barents Sea. Andreassen et al. (2004) identified several till units with chains of megablocks and rafts along the path of the Bear Island Trough Ice Stream in the Barents Sea. These sediment blocks are interpreted to have been eroded, transported and deposited by the recurring Bear Island Trough Ice Stream. We view these as similar to the features we observe (Fig. 5).

5.1.2. Arendal Terrace

The Arendal Terrace is likely to be an erosional remnant of a deposit that filled most of the deepest part of Skagerrak. The NCIS filled the 800 km long NC during the Last Glacial Maximum (LGM) (Sejrup et al., 2003; Ottesen et al., 2005), and the deepest part of the Skagerrak south of the Arendal Terrace was a convergence zone for ice streaming from northerly, northeasterly and easterly directions. The NCIS probably eroded most of the basin-fill deposit, and we interpret the Arendal Terrace (Fig. 6) as a major remnant of this erosional process. Compared to the Arendal Terrace, the ice-flow had a higher velocity in the deeper central part of the Skagerrak (Bøe et al., 2016). The submarine landforms on the surface of the terrace reflect the processes beneath the ice sheet flowing into the main trunk of the ice stream in the deepest part of the NC. The elongate ridges and depressions thus indicate the flow

direction of the ice sheet prior to deglaciation. Whereas the main trunk of the NCIS flowed towards the southwest (c. 240°), the main flow of ice across the Arendal Terrace had a more southerly direction (c. 210°) (Bøe et al., 2016).

The linked sets of individual depressions and adjacent ridges on the Arendal Terrace are interpreted as hill-hole pairs (Fig. 6). The hole or topographic depression is located on the up-glacier side of the hill. The process is seen as a continuous process of incorporating sediment slabs at the glacier bed by freeze-on, and then dumping the material close by and down-flow by subsequent melting and release. This is a similar process that is reported by Andreassen et al. (2004) in the Barents Sea. Sættem (1990) reported similar features on the Norwegian shelf, although only individual pairs were observed rather than an assemblage of many tens of pairs. The consensus regarding the formation of these glacitectonic features is that they are formed under relatively thin ice in a zone close to the glacier terminus where basal freeze-on is possible (Moran et al., 1980). On the Arendal Terrace, however, we believe that the paired landforms were produced subglacially but far from the ice margin, by at least 100 km. Whereas the velocity of the main trunk of the NCIS was high enough to erode all sediments down to the bedrock in the deepest parts of the Skagerrak, the ice velocity across the Arendal Terrace was slower and only the upper part of the pre-late Weichselian succession was removed. The slower ice movement across the terrace probably facilitated freeze-on and glacitectonic processes at the base of the glacier (Bøe et al., 2016).

5.2. Southwestern margin of ice stream

We interpret the pattern of SE-NW trending ridges and depressions on the North Sea plateau as MSGs, formed by the NCIS moving over the area (Fig. 7A,B). Whether this happened before the NCIS reached the shelf break along the axis of the NC or whether this happened during retreat is uncertain (see discussion in Section 6). Graham et al. (2007, 2011) identified MSGs in 3D seismic cubes further west in the Witch Ground Basin with a similar direction (SE-NW) which are attributed to ice flow from the Fennoscandian Ice Sheet during the LGM. The ridges and depressions with ENE-WSW trend (Fig. 7A, C) are probably MSGs, and we suggest that they reflect ice flow from southern Norway across the NC onto the North Sea plateau. These MSGs were possibly formed during the build-up phase towards LGM and before the NCIS started to operate. The dated fossils in the glaciectonized sediments c. 20 m below the sea floor on the Egersundbanken (Fig. 7) are evidence that the Fennoscandian Ice Sheet must have crossed the NC onto the North Sea plateau during the LGM. Graham et al.

(2007, 2011) have found buried surfaces with MSGs with a similar direction (NE-SW) which they attributed to ice flow from northeast.

5.3. Eastern ice stream shear marginal zone along western Norway

5.3.1. Karmsundet and outer Boknafjorden

The Karmsundet trough (Fig. 8) is interpreted as a glacially eroded overdeepening carved out by tributary glaciers flowing south and southwestwards along Karmsundet and Boknafjorden. The N-S-trend of the trough is probably due to the orientation of the underlying Karmsundet Basin with easily erodible sedimentary rocks, compared to the much more resistant crystalline rocks on both sides of the basin. Ice from the east turned southwards along the basin axis where it joined ice flowing out of Boknafjorden, and continued as a large ice stream strongly eroding the trough and carving the northern part of thick till deposits located northwest of Jæren (Fig. 8A,C,D). Sejrup et al. (1998) documented a general thick sediment cover in the Jæren area with several pre-Weichselian till units with ages up to 200 kyr BP. West of the Karmsundet trough, the ice met northwards moving ice in the NC and was deflected towards north/northwest and finally assimilated into the main trunk of the NCIS.

5.3.2. Coastal zone south of Bergen

We interpret the large ridges in the coastal zone south of Bergen (Fig. 9) to have formed subglacially in the transition zone between ice flowing out of the fjords of western Norway and the NCIS. It appears that only the upper part of the Quaternary sediment package (mostly Weichselian in age) has been remoulded and squeezed into these ridges, whereas stronger erosion has occurred between the ridges. The ridges may have been formed by an interaction of erosion of sediments between the ridges and remolding of parts of the sediments into the ridge itself. It appears that the ridges are located outside the outlets of the major fjords (partly offset). For instance, the deep Korsfjorden (up to 600 m deep) has routed large ice masses onto the shelf. Outside the zone with crystalline rocks, ridge 4 (Fig. 9) was developed along the main flow path towards the northwest, but it is offset sideways to the extension of Korsfjorden.

The flat-lying sequence above the URU represents till units deposited by the recurrent NCIS and glaciomarine or marine layered sediments that separate them (Fig. 9B). The URU represents the boundary between Quaternary sediments above and dipping sedimentary or crystalline rocks below. The linear to curvilinear depressions on top of the ridges are

interpreted as iceberg ploughmarks (Fig. 9A). These features indicate drifting icebergs during the last deglaciation of the NC and the coastal areas of western Norway. The layered deposits in the depressions between the ridges are lateglacial or Holocene sediments. Most of these were deposited during the deglaciation, but a few metres of Holocene sediments may occur on top. The small, circular and elongated depressions between some of the ridges are interpreted as pockmarks (e.g., Forsberg et al., 2007).

5.3.3. Coastal zone north of Bergen

The well-developed pattern of lineations (Fig. 10) is interpreted as MSGs generated in the transition zone by ice flowing out of the fjords of western Norway and the NCIS. The lineations initiate a few kilometres east of the boundary between Paleozoic sedimentary/crystalline basement rocks and Mesozoic sedimentary rocks, and continue into areas with a thick sequence of flat lying Quaternary sediments above sedimentary bedrock. The lineations also occur in the area of basement rocks when there is a cover of Quaternary sediments (Fig. 10B). The deepest troughs are located where the lineations turn towards the northwest and north. This is in the confluence zone where ice from mainland Norway and the NCIS merge and causes extensive erosion.

The northwest striking ridges west of the crystalline rocks northwest of Sognefjorden (Fig. 11) are interpreted as drumlins, which are partly buried below lateglacial and Holocene glaciomarine or marine sediments, especially towards the west. They are mainly formed on the lee side of basement ridges (crag and tail type features). The arc-shaped features on the flanks of some of the drumlins probably represent small slides which probably occurred shortly after the ice margin retreated (S on Fig. 11).

5.4. Central and northern Norwegian Channel and outer trough

The two large N-S trending ridges in the NC outside western Norway probably show the direction of the NCIS ice flow (Fig. 12 A, B). The ridges are probably made by soft-sediment deformation. Fig. 12C shows a transparent appearance of the sediments in one of the ridges. We think that sediments were eroded from the sides of the ridge and then squeezed into it along the flow path. The ridges resemble the ‘bundle structures’ described by Canals et al. (2000) off the Antarctic Peninsula, which they interpret as large MSGs.

At a smaller scale, the more extensive cluster of lineations (Fig. 12A) are interpreted to be MSGs formed below the NCIS showing an ice flow direction towards NNW, parallel to the trough axis.

The prograding wedges shown in Fig. 13A are interpreted as deposits at the terminus of the NC where material transported subglacially was dumped on the North Sea Fan (King et al., 1996; Sejrup et al., 2003; Nygård et al., 2005). The transparent unit (green on Fig. 13B) is interpreted as slide debrites from the Tampen Slide with an age of approximately 100 kyr BP (Nygård et al. 2005). The reflection defining the base of the Tampen Slide debrite also forms the headwall of the Tampen Slide (yellow stippled line on Fig. 13 C, D). The lowermost slide scar cuts a thick package of glacial debris flows (E on Fig. 13B) probably deposited during the third last glaciation (the Elsterian on land in Europe). Above this package, the slide scar steps up into another transparent unit (S - assumed to be of Saalian age). These two packages are separated by an unconformity (red dotted line on Fig. 13B), and it is on this surface (surface A) that the lineations shown in Fig. 13C appear. These lineations are interpreted to be MSGs formed under an ice stream during the penultimate glaciation. The lineations are mapped on this surface across most of the 3D cube (40 km), but end at the slide scar of the Tampen Slide. The overall flow direction was towards northwest (main trend 335°). The uppermost slide scar cuts a package of flat-lying sediments, deposited on the shelf by one or several ice streams during the Saalian glaciation. On a surface above this Saalian unit (the uppermost of two yellow stippled lines on Fig. 13B), a well-developed pattern of MSGs is found (Fig. 13D). The surface with these lineations is probably generated by deformation beneath the NCIS during the last glacial maximum. The general ice flow direction shown by these lineations is 342°, deviating only seven degrees from the flow direction on the Saalian surface (Fig. 13C). The MSGs shown in Fig. 13D also extend more than 10 km across the Tampen Slide scar, demonstrating that the NCIS flowed into the Tampen Slide area.

On the present-day sea-floor, we do not observe lineations from the last glaciation, probably because they are buried below a moraine ridge close to the shelf edge, or because they are destroyed by iceberg scouring. The sediments filling the scar of the Tampen Slide were dumped by the NCIS during the Weichselian. Based on core data tied to the seismic stratigraphy, Nygård et al. (2007) suggested that all the sediments above the Tampen Slide debrite were deposited during the LGM (between c. 20 and 30 kyr BP). Nygård et al. (2007) suggested at least four phases of ice stream activity when the NCIS reached the shelf break and dumped material into the slide scar within this time period.

5.5. North Sea plateau west of the Norwegian Channel

The Tampen Formation (Rise et al., 1984) is interpreted as a moraine deposited during the last glacial maximum (Fig. 15A). It is interpreted as an ice stream lateral shear margin moraine (Stokes and Clark, 2002), deposited in the transition zone between the NCIS and more passive ice on the North Sea plateau. We also observe several grounding zone wedges in the northern plateau areas west of the Tampen ridge. The outermost of these is located c. 40 km from the shelf edge (Fig. 15A), and probably locates the maximum position of the ice sheet on the plateau. In the NC, two further transverse ridges mark standstill positions during early retreat. We also observe buried MSGLs west of the NC showing ice flow towards the southwest (Fig. 14). These features document ice flow across the NC onto the North Sea plateau during a phase when the NCIS did not operate. These flow-lines are probably not from the last glaciation, but likely indicate ice sheet flow during an ice build-up phase. Graham et al. (2007, 2011) have found similar MSGLs farther southwest in the Witch Ground Basin on the UK side of the North Sea with a very similar direction (towards SW and WSW).

6. Discussion

6.1. Glacial erosional and depositional environments along the NCIS

We have constructed a map of the Late Weichselian erosion or depositional till surface along the length of the NC (Fig. 16A). This map shows the shape of the NC just after the channel was deglaciated (i.e., before deglacial sediments were deposited) and is accompanied by a conceptual model of the major flow-lines of the ice stream based on our observations (Fig. 16B). Together with our interpretations of the glacial landforms on the sea floor and seismic sections along the ice stream path, we identify three main zones along the 800 km length of the NCIS (Fig. 17): a zone where sediments were preferentially eroded, a zone where they were preferentially transported, and a zone where they were preferentially deposited.

We suggest that the initiation of high ice stream velocities occurred at the boundary between the crystalline and sedimentary bedrock. Although it is difficult to identify an ice stream signature in crystalline bedrock terrain, there is no obvious evidence for streaming velocities (e.g., bedrock mega-grooves or mega-flutes; Bradwell et al., 2008; Eyles, 2012) until the ice passed off this terrain. However, once on to the softer sedimentary bedrock and pre-existing Quaternary sediments, there is a clear erosional signature, which we characterize as Zone 1. This occurs in the first 400 km of the NCIS path, between eastern Skagerrak and outside

Stavanger, and is evidenced by numerous glacial landforms found on the seabed, e.g. overdeepened local troughs, crag and tail like forms and glaciotectonic rafts and hill-hole pairs. The Arendal Terrace is a remnant of basin fill sediments that probably covered most of the deepest parts of Skagerrak. We interpret Zone 1 as dominated by glacial erosion, where ice velocities were accelerating due to abundant subglacial meltwater. Erosion was likely accomplished by a combination of quarrying and abrasion at the boundary of the crystalline bedrock. Channelised subglacial meltwater seems also to have been important in certain areas, for example in the inner Skagerrak (cf., Graham et al., 2009) (Fig. 4).

More localised zones of erosion are also evident along the lateral flanks of the ice stream. For example, between Stavanger and the shelf edge, erosion has taken place (Figs. 8-11, 17). This area represents the confluence zone between the NCIS and ice from the mainland of Norway coming out of the fjords of western Norway and, here, extensive erosion has occurred. The zone is rather narrow (20-30 km) compared to the full width of the NC (c. 100 km) and the erosion is shown as NW-trending elongated troughs (marked as T in Fig. 9A) separated by large NW-trending ridges extending from the boundary zone between crystalline and sedimentary rocks. These troughs can reach depths up to 200 m below the surrounding terrain, extending 10 to 20 km farther west outside the boundary zone between basement and Mesozoic rocks.

Downstream of the main zone of erosion is a zone of transport along the west coast of Norway (Zone 2), where we envisage sediments from the zone of erosion are transported through a dynamic sedimentary system at the ice bed interface. The zone is dominated by mega-scale glacial lineations on the trough floor, which are likely formed as material is being transported and, potentially, deformed and streamlined into ridges (cf., King et al., 2009). Whilst there may be localized deposition/accretion associated with individual ridges (cf., Spagnolo et al., 2016), we suggest that most of the sediment that was eroded from Zone 1 is advected subglacially. Two very long ridges exist in the bottom of the NC (Figs. 12B, 16A), which indicate remoulding of sediments and possibly high ice velocities, but glacial geomorphological features are generally of much lower relief and the terrain is much smoother, perhaps enhancing or reflecting the higher velocities. We consider it most likely that as sediment is transported through this zone, MSGLs are likely to be partly depositional and partly erosional, with sediment continually being remoulded and transported along the ice stream bed. We suggest that this dynamic sedimentary system, whereby landforms are continually being remoulded and sediment fluxes are high, is similar to that recently imaged

beneath Rutford Ice Stream, West Antarctica (Smith, 1997a, b; Smith et al., 2007; King et al., 2009).

Beyond the palaeo-shelf-break (Zone 3), these ice-transported sediments were deposited on the North Sea Fan. This huge glacial trough mouth fan formed here during the Quaternary (Fig. 13). During the last glaciation the deposition was particularly large during LGM, when up to 300-400 m thick glacigenic debris flows accumulated (Nygård et al. 2005). We also suggest that the ridge at Tampen (Fig. 15), represents a lateral shear margin moraine along the western side of the channel resulting from a steady supply of sediment from the zone of transport. We suggest that similar zones characterized by erosion, transport and deposition are likely to be common to most marine-terminating ice streams in both past and present ice sheets, but that their precise spatial extent will vary due to the configuration of the underlying geology and topography.

These three zones (erosion, transport, deposition) are consistent with observations of numerous other marine-based palaeo-ice streams (Ó Cofaigh et al., 2002, 2005; Ottesen et al., 2005; Livingstone et al., 2012; Dowdeswell et al., 2014) but their extent will obviously vary depending on both ice dynamics and the underlying geology. Their identification is significant, however, because they have the ability to feedback and impact on ice dynamics. For example, intense zones of erosion in the ice onset zone are likely to locally over-deepen the bed and create a reverse bed slope, which has the potential to accelerate retreat through the inner-shelf areas (Cook and Swift, 2012; Stokes et al., 2014). In contrast, the zone of deposition has the potential to locally reduce water depths and the building of till deltas or grounding zone wedges may act to stabilize ice stream grounding-lines (Anandakrishnan et al., 2007). Over longer time-scales, it is also the case that once the accommodation space for the zone of deposition has filled, that ice streams may be forced to change their trajectory (Dowdeswell et al., 2006). In several older glaciations, the NCIS has flowed across the area which presently make up the Måløy Plateau (Fig. 1). This is evidenced by MSGLs on a deeply buried surface close to the URU (Rise et al., 2004). Above this surface, a thick sequence of flat lying units have been deposited and later also been partly eroded laterally. Thus the NCIS has changed its axis further west, and it also seems that glacial erosion has taken place along some 100 km of the outer western margin of the channel during the last glaciation (Figs. 16, 17). In the NC outside western Norway, the URU is interpreted to be very old, c. 1.1 million years according to Sejrup et al. (1995). In Skagerrak with extensive erosion into bedrock, the URU has been formed during several glaciations, but was finally formed during the LGM and is thus relatively young. This implies that the NCIS has been

erosive in different areas in different time periods. The proto-NCIS was probably first carved out outside the coast of western Norway, and then continued to erode further backwards into the Skagerrak area. We now discuss the evolution of the most recent phase of ice stream activity.

6.2. Evolution of the NCIS during the LGM

After the Ålesund Interstadial (c. 34-38 kyr BP), ice growth in the Norwegian mountains caused ice to advance southwards from the Oslofjord area and beyond the Skagerrak south and westwards to Denmark and the northern North Sea during its maximum. The Swedish and Baltic ice reached Poland, Germany and Denmark. The initial ice growth seems to have been fastest in the west, in the Norwegian mountains, whereas the ice divide slowly shifted to the east and into Sweden as the ice sheet expanded. When the ice sheet first crossed the Skagerrak and the NC, the flow was directed straight towards the south into Denmark and southwest into the North Sea. Outside western Norway, the ice sheet expanded and crossed the NC and entered onto the shallow North Sea plateau west of the NC. Fig. 14 shows MSGSLs trending NE-SW, indicating ice flow from southern Norway across the NC and onto the North Sea plateau. Comparison with data presented by Graham et al. (2007, 2010), indicates that the streamlined surface shown in Fig. 14 is probably older than the LGM, representing either an early Weichselian or an even older glaciation. The pattern probably repeats itself during every glaciation, but we have not been able to identify flow lines from LGM in any of the 3D seismic cubes we have studied west of the NC. Although robust evidence is lacking, we speculate that ice sheets during several glaciations crossed the NC during an early ice growth phase.

The first and largest LGM ice advance from Norway to Denmark in the south has been dated to 27-29 kyr BP (Houmark-Nielsen and Kjær, 2003) based on the till stratigraphy with interlayered fossil bearing beds on land in Denmark. As the ice divide shifted to the east, this resulted in a more westerly ice movement over the Skagerrak and Denmark. At this time, ice-flow from Norway and Sweden started to merge in the inner part of the Skagerrak and to flow along the NC (Longva and Thorsnes, 1997).

During an early ice stream phase, when the NCIS started to be active, the ice overspilled the NC and entered the North Sea plateau west of the channel as indicated by the MSGSLs shown in Fig. 7. Graham et al. (2007, 2011) have reported similar ice flow lineations on buried surfaces in 3D-seismic cubes farther west in the Witch Ground area. They dated this surface by correlating it to geotechnical boreholes from BGS to be younger than 26 kyr BP. They

attributed the lineations to the flow of an ice stream probably diverged from the southern part of the NCIS during the LGM and referred to this palaeo-ice stream as the Witch Ground palaeo-ice stream, sourced from the Fennoscandian Ice Sheet. Bradwell et al. (2008) have extended these flow lines all the way to the shelf edge across both Shetland and the Orkneys. Hall (2013) has recently reviewed existing data and included new data on ice flow indicators, such as striae, glacial lineations etc., on and around the Shetland Islands. He found no evidence of ice-sheet incursion over Shetland during the LGM, meaning that the ice cap over Shetland could restrain the Fennoscandian Ice Sheet after crossing the NC. In any case, the ice sheet configuration during the LGM, during both the build-up and maximum phase is poorly understood and is also complicated by the fact that the LGM is separated into an early maximum phase (c. 27-29 kyr BP) and a late phase (c. 19-24 kyr BP) with an intermediate deglaciation phase where the ice sheet reached at least the coastal areas of western Norway. As noted earlier, the detailed ice sheet configuration and its relation to the NCIS during early LGM is poorly understood. However, we suggest that one condition needed for the very dynamic NCIS to operate (cf., Nygård et al., 2007), is ice support on the North Sea plateau west of the NC. This is also evidenced both by the lateral ice stream shear margin moraine on the North Sea plateau (the Tampen moraine), but also by a series of grounding zone wedges and retreat moraines on the North Sea plateau west of the Tampen moraine (Fig. 15), which document that an ice sheet has covered the North Sea plateau east of Shetland. The break-up of the NCIS in the much deeper outer parts of the NC, must have been much faster than the retreat of the more passive ice on the shallow North Sea plateau.

7. Conclusions

Several regional and detailed multibeam bathymetric data sets together with 2D and 3D seismic data reveal a variety of glacial landforms and processes along the 800-km-long path of the Norwegian Channel Ice Stream bed, which we differentiate into three main zones. The first 400 km of the inner and mid-shelf (Zone 1) are characterized by an erosional landscape and a major overdeepening. In eastern Skagerrak, in the onset zone of the ice stream, the NCIS has eroded and displaced huge sedimentary bedrock blocks, up to 4 km x 8 km x 30 m in size. In the same area, hairpin erosional marks, up to 5 km long, 1 km wide and 40 m deep indicate that, in addition to large-scale glaciotectonism, high pressure meltwater may have been an important agent of erosion. This zone of erosion is succeeded by the approximately 400 km long zone 2 where we interpret that sediments from Zone 1 were primarily

transported, rather than being eroded or deposited. Zone 2 is characterized by mega-scale glacial lineations which we interpret to be formed in a dynamic sedimentary system dominated by high sediment fluxes, but with localized deposition and accretion. Towards the shelf break, the North Sea Fan extends to the deep Norwegian Sea, and reflects massive sedimentation of glacial debris onto the continental slope (Zone 3, predominantly deposition). Numerous glacial debris flows accumulated, constructing an up to 400 m thick unit during the Last Glacial Maximum. MSGs on buried surfaces in 3D seismic cubes show ice flow across the Norwegian Channel and onto the North Sea plateau, probably from an ice-build up phase before the NCIS started to operate. Other MSGs are identified on two buried surfaces on the North Sea Fan from the last and second last glaciation, document ice flow towards NNW on both surfaces.

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FIGURE CAPTIONS

Fig. 1: Overview map with location of other figures. Bathymetry from the Norwegian Hydrographic Service and Olex AS. AT - Arendal Terrace, B - Boknafjorden, K - Karmsundet, MP - Måløy Plateau, NSF - North Sea Fan, S - Stavanger, St - Statfjord. Stippled line locates seismic line in Fig. 13A.

Fig. 2: Overview of different bathymetric and side scan sonar data sets used in the study. MBB - multibeam bathymetry, SBB - single beam bathymetry, NGU - Geological Survey of Norway, NHS - Norwegian Hydrographic Service, FFI - Norwegian Defense Research Establishment, PGS - Petroleum Geo-Services.

Fig. 3: Elongate ridges emanating from the edge of the crystalline bedrock in eastern Skagerrak from the onset zone of the NCIS (location shown on Fig. 1). MBB 10 m grid.

Fig. 4: (A) Colour-shaded relief bathymetry (50 m grid) of the southeastern parts of Skagerrak with hairpin erosional marks and large depressions (D) showing large-scale glacial erosion (where large slabs of bedrock were eroded by the ice stream). (B) Bathymetric profiles across two hairpin marks.

Fig. 5: (A) Shaded-relief bathymetry (50 m grid) of eastern Skagerrak showing a series of glaciotectionic rafts. White rectangle locates panels (C) and (D). (B) Shaded-relief bathymetry with interpreted glacial features. (C) Colour-shaded bathymetric map indicating the glaciotectionic features. (D) Same as in (C), but where depression and rafts are marked. (E) Seismic air gun profile (NGU9101066) across glaciotectionic raft located just above the bedrock surface. The raft is up to 35 m thick (40 ms) and 1800 m across and is draped by c. 70 m of fine-grained sediments mimicing the underlying morphology. Red arrows mark the surface with MSGLs. ms - milliseconds.

Fig. 6: (A) Arendal Terrace (erosional remnant after the basin fill in the Skagerrak basin has been eroded by the NCIS). (B) Seismic air-gun profile across parts of the terrace. (C) Geopprofile across the terrace showing where the NCIS has eroded the basin fill sediments of Skagerrak. (D) Detail with 2 m depth contours.

Fig. 7: (A) Seabed sediment map covering parts of the eastern North Sea plateau and the adjacent Norwegian Channel (modified from Ottesen et al., 1999). (B) Side-scan sonar image from an area with MSGs towards northwest (location shown as a black cross). (C) Side-scan sonar image with possible MSGs towards southwest (location shown as a black cross). (D) Lithological logs of two cores from geotechnical boreholes on Egersundbanken, eastern North Sea plateau (Yme oil field, block 9/2). (E) Core sections from geotechnical borehole BH1004 on Egersundbanken. (1) Photo of core interval 19.40-19.60 m below the seabed. Note the deformed and tectonized nature of the sediments. (2) Line drawing of core interval 23.07-23.47 m below the seabed. Note the tectonized nature of the core interval, with folding, faulting and shearing of the sediments (main shear direction into the page). (3) Photo of core interval 23.07-23.27 m in (2). See Fig. 7A for location of borehole BH1004 and Fig. 7D for complete core log.

Fig. 8: (A) Regional bathymetry of Karmsundet (K) and surrounding areas. (B) SW-NE seismic profile across Karmsundet showing crystalline rocks on both sides and infill of thick lateglacial and Holocene layered sediments. Note that the till is very thin or absent. (C) Seismic N-S profile showing glaciomarine and Holocene sediments deposited in the basin above both crystalline and sedimentary bedrock (Mesozoic rocks). (D) Interpreted profile shown in C.

Fig. 9: (A) Bathymetric map from coastal areas south of Bergen showing several large ridges curving towards the northwest (crest marked with white stippled lines). The ridges are developed in the transition zone between ice coming out of the fjords of western Norway and the NCIS. The numbers refer to ridges described in the text. K-Korsfjorden, S-Selbjørnsfjorden. T - trough. Black areas - shallow water, not mapped. (B) Seismic profile illustrating glacial erosion into the sedimentary bedrock directly west of crystalline bedrock. Seismic line X-X' - NPD-Kyst-6-96A.

Fig. 10: (A) Sea-floor morphology with MSGs north of Bergen showing how the ice coming out of the west Norwegian fjords was deflected towards north and assimilated into the NCIS. Black areas - shallow water, not mapped. (B) Seismic line (NPD-Kyst-96-115). Q - Quaternary sediments above crystalline bedrock.

Fig. 11: Multibeam bathymetry (2 m grid) from the Norwegian Channel northwest of Sognefjorden showing drumlins west of the boundary between crystalline and sedimentary rocks (stippled white line). Note the small slides (S). See Fig. 1 for location.

Fig. 12: (A) Interpreted LGM surface below Holocene and glaciomarine deposits (yellow horizon in (C) in 3D seismic cube L09 (part of PGS megasurvey). The surface shows an extensive pattern of MSGs (red stippled lines) and iceberg ploughmarks. Note the large ridge (NNW-SSE trend) shown by the 20 ms depth contours. This ridge is shown in the overview map (Fig. B) as the westernmost of two red stippled lines. (B) Regional bathymetry of parts of the Norwegian Channel with 10 m contours showing two large ridges (red stippled lines) in the channel parallel to the channel axis. (C) Seismic profile X-X' across the area. The interpreted LGM till surface is coloured yellow. URU- Upper Regional Unconformity. Profile X-X' is located in Fig. A. S - Sognefjorden.

Fig. 13: (A) Interpreted seismic profile SPT-94-406 (location shown on Fig. 1) across the outer part of the Norwegian Channel and the upper part of the North Sea Fan. Yellow - glacial debris flows deposited by the NCIS. Green and orange - slide deposits. Pink - Saalian transparent glacial sediment package. URU - Upper Regional Unconformity. Base NSF marks the onset of deposition of glacial debris flows on the North Sea Fan (from Nygård et al., 2005; Ottesen et al., 2014). Base Naust reflector from Ottesen et al. (2009). (B) Detailed seismic profile from PGS 3D seismic cube MOS2007 showing the slide scar of the Tampen Slide and glacial sediments deposited by the NCIS. E-Thick transparent unit from the third last glaciation. S-Transparent unit from the second last glaciation. (C) Interpreted surface A (location shown in Fig. B) in a 3D seismic cube showing MSGs from the Saalian glaciation. (D) Interpreted surface B (location shown in Fig. B) in a 3D seismic cube showing MSGs from the Weichselian glaciation. The headwall of the Tampen slide is marked with a yellow stippled line in C and D.

Fig. 14: (A) Time slice (260 ms depth) from the 3D seismic cube H08 from PGS's megasurvey. (B) Same as in A but with interpretation showing a series of MSGs (yellow lines) and two buried and filled tunnel valleys (T1 and T2). (C) Seismic line across the area showing the shallow stratigraphy and location of the time slice (white stippled line).

Fig. 15: (A) Bathymetry of the Tampen area showing the Tampen Ridge (blue dotted line) interpreted as a lateral ice stream shear margin moraine. White arrows mark the outermost grounding zone wedge (GZW). R- moraine ridge in the NC. M - small moraine ridges on the North Sea plateau. Depth data: 50 m grid from Olex. (B) Geoprobe across the Tampen Ridge (modified from Skinner et al., 1986). TAM - Tampen Formation, SPE - Sperus Formation, CSO - Cape Shore Formation, FD - Ferder Formation, MRN - Mariner Formation, SHN - Shackleton Formation. mbsl - metres below sea level.

Fig. 16: (A) Interpreted late Weichselian erosion surface (ms twt) showing the shape of the Norwegian Channel at the start of the deglaciation. Modified and extended from Rise et al. (2008). Black dotted lines show elongated ridges on the LGM surface described in the text. (B) Conceptual model of flow-lines of the Norwegian Channel Ice Stream, illustrating that ice from different catchment areas drain into the Norwegian Channel and is likely separated along the channel. The boundary between different flow lines is located above the large elongated ridges on the sea floor. Blue dotted line - present shelf edge, green stippled line - lateral ice stream shear margin moraine.

Fig. 17: (A) Map showing zones of erosion, transport and deposition along the Norwegian Channel with mapped glacial features from the sea floor. (B-C) Geoprobe across the Norwegian Channel. (D) Length profile (X-X') along the axis of the Norwegian Channel with areas of mainly erosion, transport and deposition of sediments by the Norwegian Channel Ice Stream during the LGM.